

A SAMPLE HANDLING, ENCAPSULATION, AND CONTAINERIZATION SUBSYSTEM CONCEPT FOR MARS SAMPLE CACHING MISSIONS

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ABSTRACT

A Sample Handling, Encapsulation, and Containerization (SHEC) subsystem capable of caching functions for proposed future Mars sample caching missions is described. The SHEC system concept consists of a canister carousel, handling arm, and bit carousel. Samples are acquired by placing individual sample tubes into separate core bit assemblies (CBAs), which are attached to an arm-mounted Sample Acquisition Tool (SAT) that cores samples directly into the tubes. The current SHEC prototype configuration has the capability to collect 19 samples of approximately 1 cm diameter by 5 cm long. A proof of concept prototype of the SHEC subsystem was built and tested at the Jet Propulsion Laboratory, and a TRL 4 level design is currently in development.

1. INTRODUCTION

Proposed future Mars sample caching missions would require technology to acquire, encapsulate, and cache core samples into a container capable of being delivered back to Earth. The Mars Exploration Program Analysis Group (MEPAG) has highlighted the importance of collecting samples on Mars for potential Earth return [6], and current concepts for the proposed Mars Astrobiology Explorer-Cacher (MAX-C) mission baseline a sample caching subsystem [11] (see Fig. 1). Studies on Mars Sample Return (MSR) architectures have been performed and are described in [9] and [12], along with system level concept designs.

In FY'09, a 3-year Integrated Mars Sample Acquisition and Handling (IMSAH) task was initiated at the Jet Propulsion Laboratory (JPL) to develop technology to acquire and cache core samples for possible future MSR missions. This paper discusses previous research efforts pertaining to Mars sample acquisition and caching, design elements and requirements, a trade of various caching subsystem approaches, and the current Sample Handling, Encapsulation, and Containerization subsystem (SHEC) being developed under the IMSAH task at JPL.

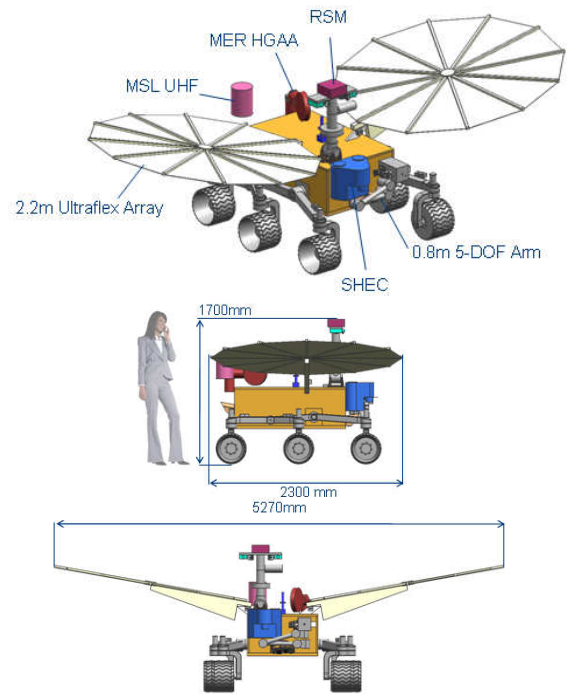


Fig. 1. Concept for Mars Astrobiology Explorer-Cacher (MAX-C) with a caching subsystem (SHEC)

2. BACKGROUND

Methods for caching samples for Mars sample return have been researched and proposed in the past, but were never flown on a mission. These designs were studied as part of the IMSAH task.

2.1 Previous Sample Caching Designs

The Athena Rover proposed for the 2003 and 2005 Mars Sample Return Missions planned to have a body-mounted rotary drag mini-corer capable of taking 8 mm cores of 25 mm in length, as shown in Fig. 2. The rover was expected to collect 50-60 rock and soil cores from 20 sites, with a collected estimated mass totalling 250 g of sample to return to Earth. Sample tubes would be carried in a set of carousels that would be rotated to accept samples ejected from the mini-corer (see Fig. 3).

The tubes would be sealed, driven to the lander, and dropped from the bottom of the mechanism into the Orbiting Sample Canister (OSC) [1]. The mini-corer and caching system, however, were not implemented in the flight design of the rover.

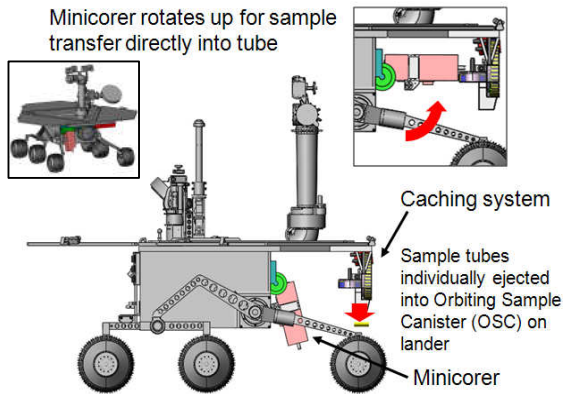


Fig. 2. Proposed Mars Sample Return 03/05 sample acquisition and caching.

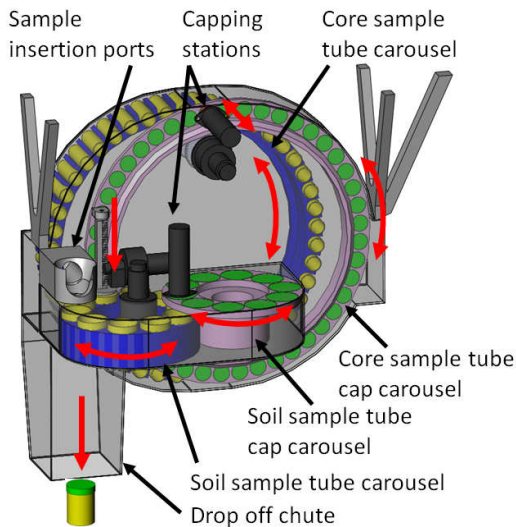


Fig. 3. Proposed Mars Sample Return 03/05 sample caching system.

Mars Science Laboratory funded the development of a sample cache container capable of accepting 5-10 rock samples, each around 0.5-1.5 cm across, from an arm-mounted scoop (see Fig. 4) [2]. A grasping feature was designed onto the container for a manipulator to remove it from the rover. Tabs holding the container to the cradle would bend away when the container is pulled out with a predetermined force.

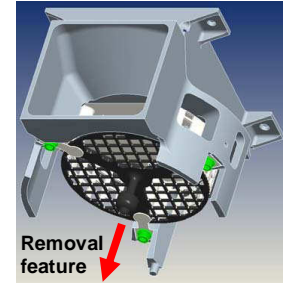


Fig. 4. Sample cache proposed for Mars Science Laboratory.

2.2 Previous Sample Caching Research

The Jet Propulsion Lab developed a concept for a Sample Cache Subsystem (SCS) designed to transfer and store core and soil samples (see Fig. 5) [3]. Sterile sample tubes are stored in a cache container. A two-degree-of-freedom transfer arm removes an empty tube from the container and places it into the sample transfer funnel, where the sample core is fed into the tube by the drill. The transfer arm then removes the filled sample tube, and places it back into the cache container where it is capped. A similar concept using flexures to retain the sample tubes and a heating station to seal the samples is shown in Fig. 6. Additional focused studies regarding sample sealing are discussed in [4] and [5].

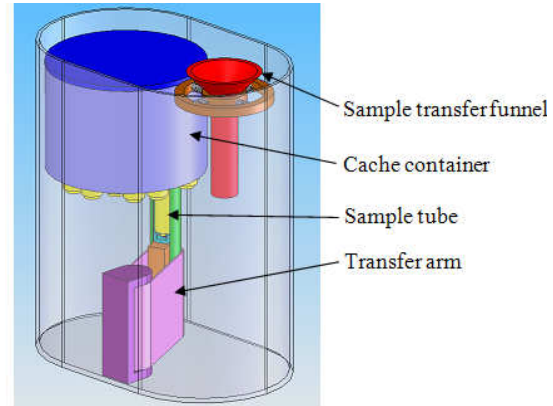


Fig. 5. Sample Caching Subsystem in [3].

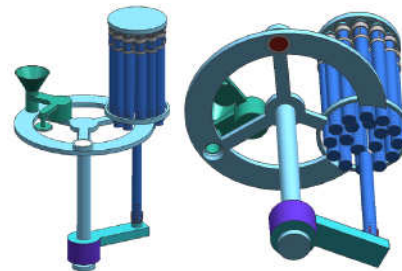


Fig. 6. Containerization system concept in [8].

3. SYSTEM COMPONENTS

The current proposed Mars Sample Return architecture calls for a prospector rover to acquire a suite of samples for return to Earth. A coring drill would acquire the core samples, which could be stored in sample tubes, sealed with a cap or plug, placed into a single cache container, and either delivered to a lander or collected by a fetch rover sent during a subsequent mission. Fig. 7 shows the sample caching components, as well as their possible interactions with one another.

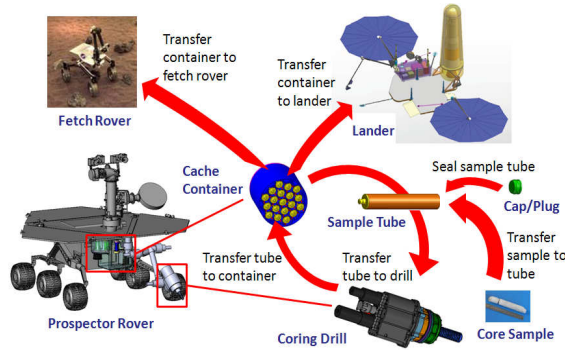


Fig. 7. Sample transfer system components and interfaces.

4. DESIGN DRIVERS

Design requirements were developed from the latest science objectives of the Mars Exploration Program Analysis Group (MEPAG), input from proposed caching rover requirements (such as the MAX-C mission concept), expected operating conditions, and hardware design to help optimize power, mass, and volume costs.

4.1 Science Objectives

The Mars Exploration Program Analysis Group (MEPAG) developed a set of high-level scientific objectives for an MSR mission and provided recommendations on the type of samples desired [6]. Guided by the science priorities outlined by MEPAG, along with input from the current sample suite chosen for the 2011 Mars Science Laboratory rover, the following sample acquisition requirements were derived for the IMSAH task:

- Acquire rock cores with dimensions approximately 1 cm wide by 5 cm long (based on a 10 g mass of a basalt sample).
- Acquire at least 20 rock cores for return (limited by the size of the sample canister).

- Be able to acquire samples from Saddleback Basalt, Volcanic Breccia, Siltstone, Limestone, and Kaolinite.

4.2 Sample Canister Constraints

Concepts for Mars Sample Return rely on a sample canister that could be contained in an Orbiting Sample Canister (OSC), which could be transported off Mars in a Mars Ascent Vehicle (MAV), and returned to Earth in an Earth Entry Vehicle (EEV) [9, 10, 12]. Fig. 8 shows an artist's conception of the OSC alongside the MAV. Fig. 9 shows the OSC inside the EEV. The cylindrical volume in the center represents the allotted space for the sample canister. To be reasonably compatible with the current proposed OSC dimension, the canister dimensions are kept to a maximum of 7 cm outer diameter by 7.5 cm high for the IMSAH design.

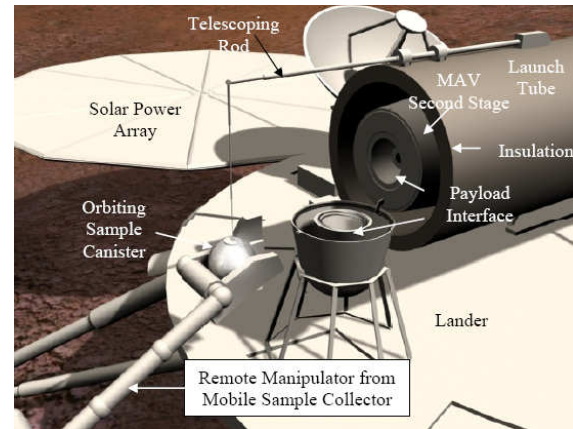


Fig. 8. Conceptual image of the Orbiting Sample Canister on Mars [9].

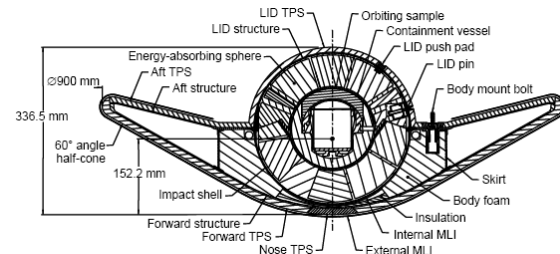


Fig. 9. Proposed Earth Entry Vehicle [10].

4.3 IMSAH System Architecture

Requirements were derived for the IMSAH task based on input from the science community and Mars Program Office at JPL. This includes expected rover operating conditions and sampling configurations. The key system-level components are shown Fig. 10. The baseline system architecture for sample acquisition and handling for IMSAH include:

- Tool Deployment Device:
 - Design: 5 DOF arm.
 - Functions: Tool deployment, alignment and linear feed; canister placement on the ground.
- Sample Acquisition Tool:
 - Technique: Rotary percussion.
 - Functions: Coring, breakoff, retention, bit changeout, linear spring for preload and vibration isolation.
- Caching Subsystem:
 - Sample Encapsulation: Sample acquisition directly into the sample tube in the bit.
 - Sample Transfer: Bit changeout to transfer sample to caching subsystem (sample in tube in bit).
 - Functions: Sample tube transfer in/out of bit, bit changeout, tube sealing, tube storage in canister.

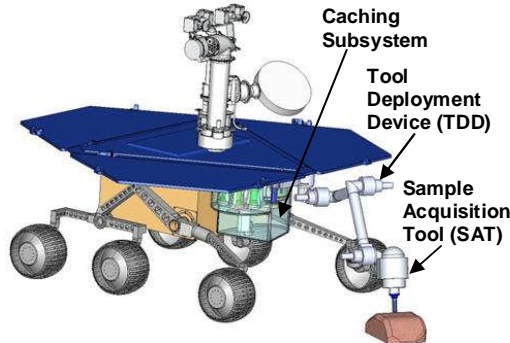


Fig. 10. IMSAH configuration for prospector rover.

4.4 Caching Subsystem Requirements

The following requirements were developed for the caching subsystem as part of the IMSAH task:

- Store samples in individual sample tubes.
- Seal samples in sample tubes to prevent material loss through the seal.
- Fill the sample canister such that it could be returned to Earth (i.e., close-packed).
- Be able to place the sample canister on the ground.
- Allow tubes to be removed from the container for repackaging by another handling system, e.g., on a future lander.

Additional system level requirements that drive the sample caching subsystem:

- Be sized to operate on a MER-class rover of mass less than or equal to 300 kg.
- Be able to reject a sample after acquisition.

- Perform sample handling and caching operations while on slopes up to 25 degrees.
- Total sample acquisition time including tool deployment and extraction from the rock would occur within one Mars daylight period.
- Measure the sample with 50% volume or mass accuracy.
- Minimize sample contamination to satisfy Planetary Protection and Contamination Control requirements.

5. CACHING SUBSYSTEM OPTION SPACE

Various high-level designs for sample acquisition and caching were looked at. Fig. 11 lays out possible sample transfer options and implementations. A detailed analysis of this concept is reviewed in [7]. These designs for the caching subsystem were narrowed down to four sample transfer options based on whether the sample acquisition tool (SAT) delivers a raw core or core in a tube to the caching system, and whether the samples are directly delivered by the SAT into the sample canister or indirectly through an intermediate transfer station. All designs assume that the core samples must be stored in separate sample tubes, sealed with caps or plugs, and packed into a single removable cylindrical sample container.

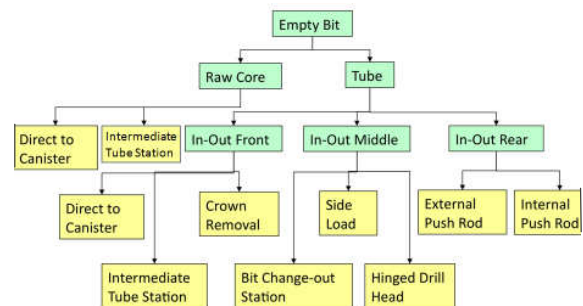


Fig. 11. Focused trade space.

5.1 Direct Core Transfer

The direct core transfer model assumes a raw core is deposited from the SAT directly into a tube contained in the sample canister through a single sample insertion port (see Fig. 12). The sample tube carousel rotates the filled tube over to the sealing station, where a linear actuator presses a plug from the plug ring into the tube, sealing it. A separate bit carousel houses the drill bits. This concept is similar to the ATHENA rover caching system for the proposed 03/05 Mars Sample Return Mission (Fig. 3), except the plugs are arranged in a 2D pattern instead of a single plug ring to accommodate a close packed sample canister.

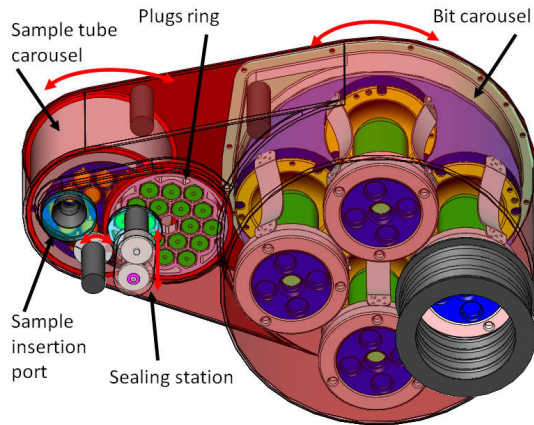


Fig. 12. Direct core transfer caching subsystem.

5.2 Indirect Core Transfer

The indirect core transfer configuration assumes a raw core is pushed out from the SAT into a sample tube at an intermediate sample transfer station first (see Fig. 13). The filled tube is then removed from the station, sealed, and transferred to the sample canister using a dedicated handling arm. The sample transfer station could be placed on the same bit carousel as the drill bits. This design is based on the Sample Caching Subsystem (SCS) described in [3].

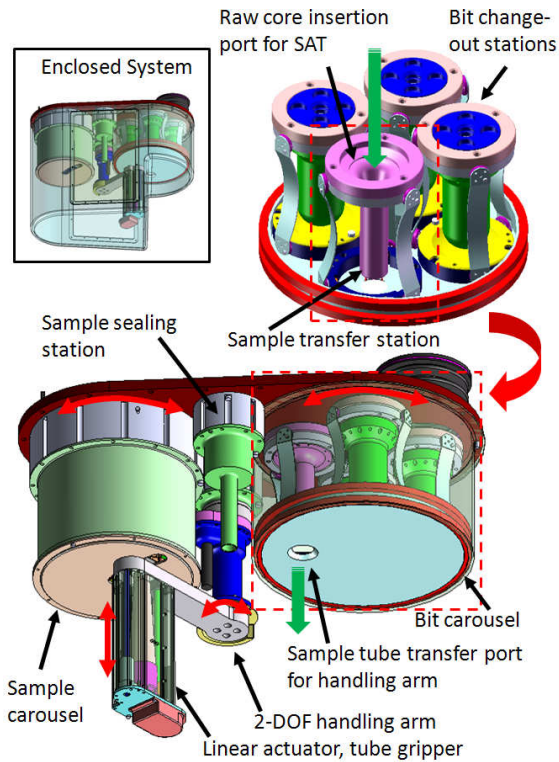


Fig. 13. Indirect core transfer caching subsystem.

5.3 Direct Tube Transfer

The direct tube transfer design requires the SAT to remove a sample tube directly from the sample canister, core a sample into the tube, and insert the filled tube directly back into the sample canister (see Fig. 14). Upon inserting the sample tubes in the canister, the tubes would be pushed onto plugs or caps at the base of the canister to seal the sample.

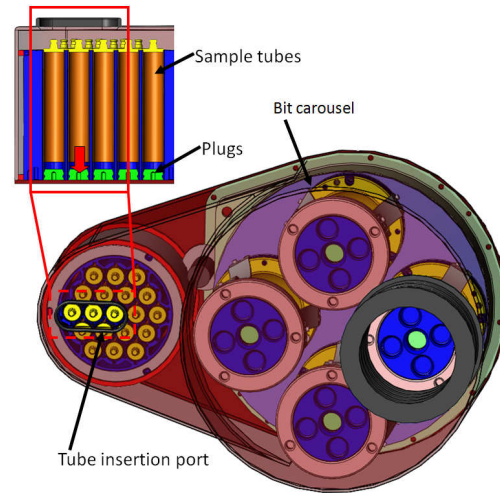


Fig. 14. Direct tube transfer caching subsystem.

5.4 Indirect Tube Transfer

The indirect tube transfer concept requires a dedicated handling arm to transfer an empty sample tube into a core bit assembly (CBA) (see Fig. 15). The sample acquisition tool could then connect to the CBA, core a sample into the tube, and place the CBA back onto the bit carousel. The handling arm then removes the filled sample tube from the CBA, plugs and seals the tube, and places it back into the sample canister.

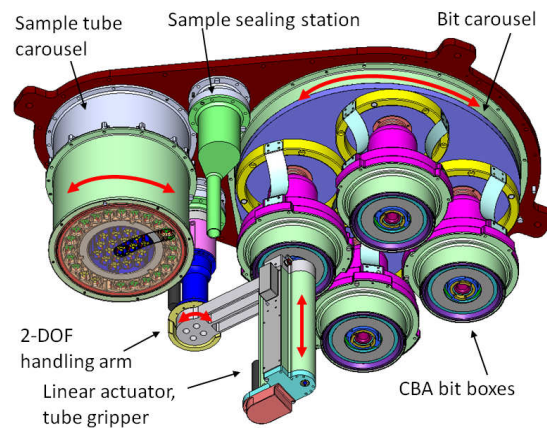






Fig. 15. Indirect tube transfer caching subsystem.

5.5 Caching Subsystem Trade Study

Each of the four caching systems were studied and traded. Important factors in deciding which design to use were robustness to broken cores, compatibility to a close-packed canister, susceptibility to sample contamination, and system mass contribution (see Tab. 1).

Table 1: Sample Caching Options Analysis

		Robustness to Broken Cores	Close Packing	Sample Contamination	Mass (consider system mass)
Direct Core Transfer		Low, transfers raw core ↓	Transfer with large arm limits precision ↓	More exposed, increases risk ↓	Low mass, but drill needs a push rod ↔
Indirect Core Transfer		Low, transfers raw core ↓	Transfer with small arm increases precision ↑	Less exposed, decreases risk ↑	Medium mass, but drill needs a push rod ↓
Direct Tube Transfer		High, transfers tube ↑	Transfer with large arm limits precision ↓	More exposed, increases risk ↓	Low mass, but drill needs a push rod and tube gripper ↔
Indirect Tube Transfer		High, transfers tube ↑	Transfer with small arm increases precision ↑	Less exposed, decreases risk ↑	Medium mass, reduces drill functions (mass) ↔

Robustness to broken cores describes the system's ability to perform sample transfer in cases where the cores are split or composed of pucks. The direct core transfer and indirect core transfer methods both rely on a push rod in the drill to eject the core from the drill bit into a separate sample tube. There is a possibility of jamming as the core is pushed, as well as when it is transferred between the tube and drill bit. The direct tube transfer and indirect tube transfer methods collect the sample directly into the tube, mitigating this risk.

Close packing describes the ability to store the sample tubes tightly in a sample container. The closer the tubes are packed, the more precise the sampling or tube transfer arm must be. In the direct transfer methods, the arm performing the coring must also perform the transfer operation. Based on how stiff and precise this mechanism can be built would limit how close the samples could be packed in the canister. The indirect methods utilize a smaller, dedicated precision transfer arm, allowing sample transfer into a closer packed canister.

To limit contamination of the sample, reducing exposure of the sampling hardware to the outside environment, as well as limiting the number of surfaces the sample touches is important. In the core transfer methods, the core is exposed to multiple surfaces, including the inside of the coring bit and the push rod.

This increases exposure to contamination from the outside environment, as well as cross-contamination between samples. With the tube transfer methods, the core is collected directly into the sample tube, greatly reducing contamination risks.

Contribution to system mass distributed between the drill and caching subsystem was investigated. The direct transfer methods have the possibility of being lightest due to the absence of an additional handling arm. However, these two methods, along with the indirect core transfer method, also require the drill to have a push rod, adding more mass to the drill, as well as possibly requiring a heavier arm to support the additional drill mass. Additionally, the direct tube transfer method requires the drill to have a tube gripper to hold onto the tube during drilling and tube transfer. The indirect tube transfer system, on the other hand, does not require the drill to have a push rod nor a tube gripper, helping reduce total mass on the drill and arm.

After performing the above trades, the indirect tube transfer configuration (Fig. 15) was chosen for the Sample Handling Encapsulation and Containerization (SHEC) subsystem. Benefits of this system include:

- Robustness to sampling broken cores by not requiring the cores to also be transferred between the coring bits and separate sample tubes.
- Utilization of a precise handling arm to allow sample transfer into a close-packed canister.
- Reduction of sample contamination by limiting sample exposure to external surfaces and collecting the cores directly into sample tubes.
- Possible lowering of overall system mass by removing the requirement for the coring drill to have a separately actuated push rod.

Additionally, the SHEC subsystem takes advantage of the requirement for bit change-out, utilizing the bit carousel to rotate detached core bit assemblies to the handling arm to transfer sample tubes in and out.

6. SHEC OVERVIEW

The SHEC subsystem concept consists of a canister carousel, handling arm, and bit carousel, as shown in Fig. 15. The canister carousel rotates a canister containing sample tubes sized for 1 cm diameter by 5 cm long cores, spare sample tubes, and sample tube plugs. The bit carousel rotates a platform of four core bit assemblies (CBAs), which could be attached to and detached from the SAT. During sample acquisition, the handling arm removes an empty sample tube from the sample canister and places it into a CBA. The SAT attaches to and removes the CBA, cores a sample, and

places and releases the CBA back into the SHEC. The handling arm removes the filled sample tube from the CBA, seals it with a plug, and places it back into the sample canister. Fig. 16 shows the preliminary dimensions for the SHEC, and Fig. 17 shows a bottom view with the various handling arm stations. Additional sensing stations may also be placed along the handling arm path to analyze the end of the core before sealing the tube.

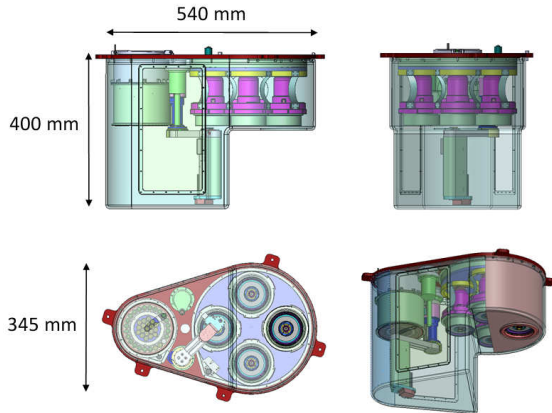


Fig. 16. SHEC subsystem measurements.

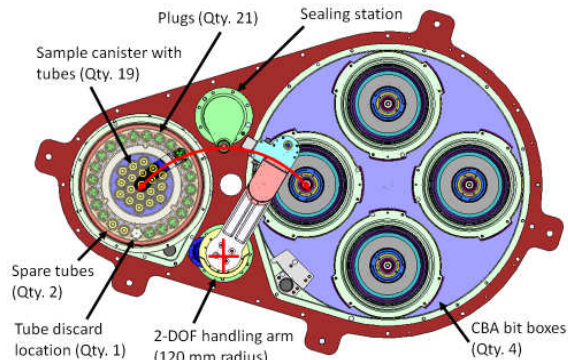


Fig. 17. SHEC handling arm stations.

7. CONCEPTUAL SHEC OPERATIONAL SEQUENCE

Sample handling is performed by the SHEC with the following ten step procedure shown in Fig. 18:

1. The handling arm rotates to the canister carousel and removes a sterilized sample tube.
2. The handling arm rotates to a core bit assembly (CBA) and places the sample tube into the core bit.
3. The bit carousel rotates the CBA with the sample tube to the bit transfer port.
4. The arm-mounted sample acquisition tool (SAT) docks with the SHEC and attaches to

the CBA.

5. The SAT removes itself from the SHEC to perform a coring operation. As the SAT cores into a rock, the core enters the sample tube inside the bit.
6. The SAT docks with the SHEC and detaches from the CBA.
7. The bit carousel rotates the CBA back to the tube transfer location, where the handling arm removes the filled sample tube.
8. The handling arm rotates to the plug ring and pushes the sample tube up onto a plug to both seal the sample tube and measure how much sample was collected.
9. The handling arm rotates to the sealing station and presses the plug against a heater, where it could be soldered to the inside of the tube for possible hermetic sealing.
10. The handling arm rotates back to the sample canister and inserts the sealed tube back into its cartridge.

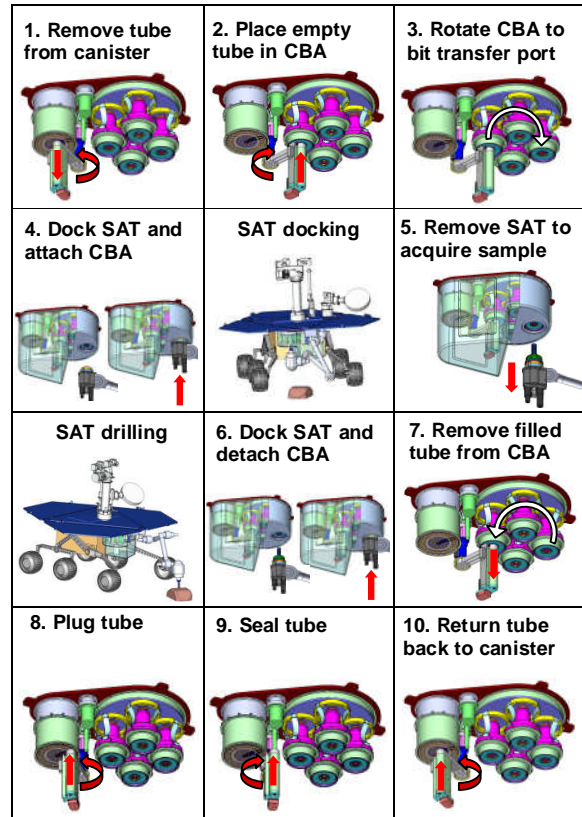


Fig. 18. SHEC operational sequence.

After the operation is complete, the sample carousel rotates new sample tubes and plugs into place for subsequent sampling. The canister carousel also contains spare sample tubes. If a particular sample could not be plugged and sealed properly, or if the

sample is determined not desirable for retention, the particular tube along with the sample could be discarded into the tube discard location, shown in Fig. 17. Another sample could be taken with one of the spare tubes, and stored in the sample canister as a replacement. In addition, if another more desirable sample is found after all tubes in the sample canister are filled, the sample could be collected by in spare tube and swapped with one of the existing tubes in the canister.

7.1 Sample Encapsulation

The core samples are stored in a sample tube and sealed with a plug (see Fig. 19). The inside length of the tube is 66 mm deep, allowing for a 50 mm core, 6 mm plug, and 10 mm gap for fines or irregular core profiles. The plug has two seals: a spring-loaded Teflon seal and a low-temperature solder seal. The Teflon seal is robust to any dust layer along the inner wall of the tube, could provide a particle seal, and could provide around a 5 N plug retention force, enough to retain a 10 g sample during rover mobility and MAV launch alone. The secondary solder seal has the potential to provide gas tight sealing of the sample, as well as retain the sample during an estimated 3500 g Earth impact seen by the Earth Entry Vehicle (EEV) upon return [10]. Preliminary testing of soldering for sealing pristine sample tubes is described in [4]. Further testing remains to be done to determine seal capability, effectiveness, and strength of soldering in tubes used for actual sample collection.

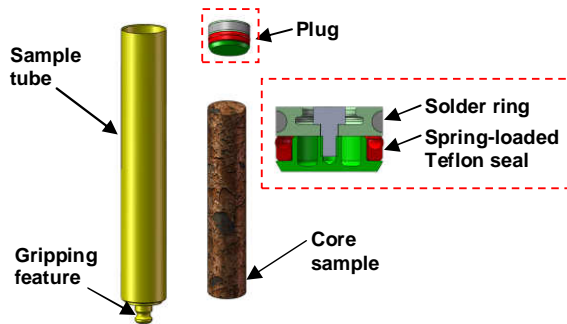


Fig. 19. Sample tube, core, and plug.

The sample tubes are transferred and sealed using a dedicated handling arm in the SHEC, shown in Fig. 20. The handling arm consists of a rotational actuator to move between the stations shown in Fig. 17, and a linear actuator to insert and remove the sample tubes from the CBAs and canister cartridges, as well as perform the plugging and sealing operations. A tube gripper raised and lowered by the linear actuator grips onto a feature on the back of the sample tube during transfer operations using a ball lock. A force-torque sensor at the base of the handling arm could be used to

set a desired preload when inserting the tube into the CBA, as well as help determine when the plug is seated against the sample during sealing and sample measurement.

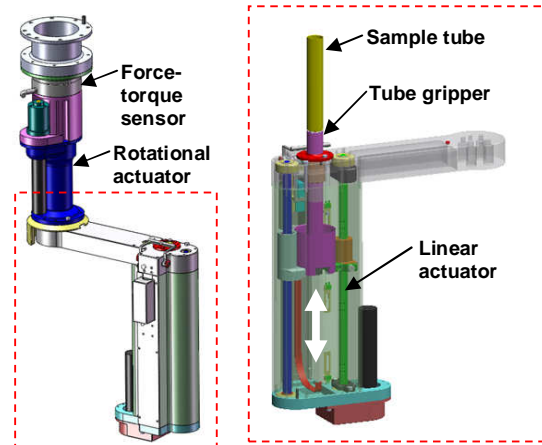


Fig. 20. SHEC handling arm.

To remove a tube from the sample canister, the handling arm is rotated to the canister and positioned under a desired tube. The tubes are held in the canister with three retention clips made of spring-tempered steel. As the tube gripper approaches the tube, these clips are displaced, freeing the tube. To remove the tube, the tube gripper actuates a ball lock onto a gripping feature on the back the tube and then retracts the tube with the linear actuator into the handling arm (see Fig. 21). When placing the tube back into a cartridge, the procedure is reversed. Three spring fingers grip the sides of the tube and secure it vertically while the tube gripper is removed until the tube retention clips pop back into place. Similar operations are performed for the spare sample tubes, as well as during insertion and removal from the CBAs.

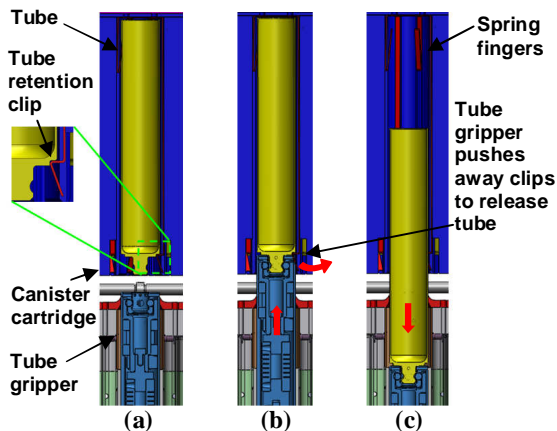


Fig. 21. Removing a sample tube from the sample canister: (a) Tube gripper positioned under sample tube, (b) tube gripper extended to and attached to tube, (c) tube retracted from canister into handling arm.

After the SAT has acquired a sample with the tube and the handling arm has removed the tube from the CBA, the handling arm rotates the filled tube to the plug ring. To plug the tube, the linear actuator presses the tube onto a plug (Fig. 22). Once the plug is fully inside the tube, the linear actuator continues to press the tube up against the plug rod, seating the sample against the base of the tube and preloading the plug onto the sample to secure and preserve its structure. Preloading of the sample could be determined either through the force-torque sensor or through current sensing. The distance the plug was pressed into the tube is measured by the linear actuator and used to estimate sample volume.

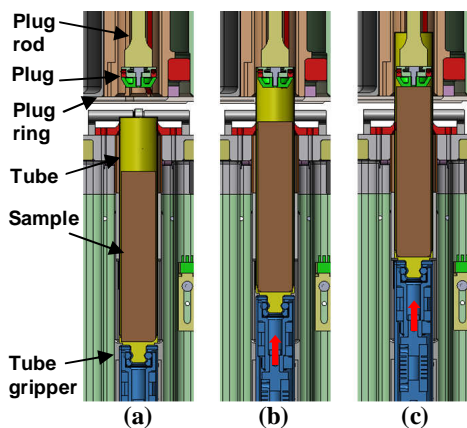


Fig. 22. Sample tube plugging operation: (a) Filled sample tube positioned under plug, (b) tube extended onto plug, (c) tube further extended to fully seat core sample and plug in tube.

After the sample tube has been plugged, the handling arm rotates to the sealing station, where the tube is

pressed against a heating element. The heating element only applies heat near the solder ring of the plug, and provides the lowest amount of heat over the needed time for the solder to melt and form a seal, limiting any heat exposure to the sample itself (Fig. 23). Once complete, the sealed sample tube is placed back into the sample canister.

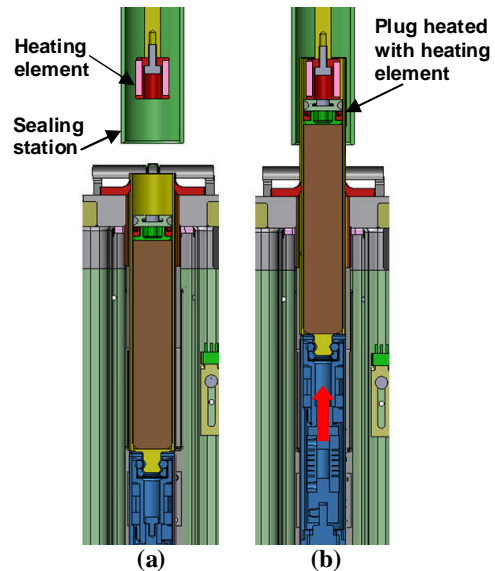


Fig. 23. Sealing operation: (a) Plugged sample tube positioned under sealing station, (b) tube extended up to heating element and sealed.

7.2 Bit Changeout

The SHEC utilizes bit changeout to insert and remove sample tubes for sample acquisition. Each core bit assembly (CBA) is secured in a bit box using a ball lock. The SAT rotates the ball lock cam to lock and unlock the CBA through a pair of vertical pins that interface with the features on the bit box (see Fig. 24).

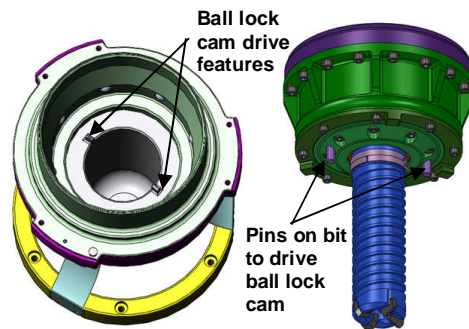


Fig. 24. CBA bit box ball lock interface.

To change out a bit, the SAT docks the CBA with the bit box, slowly rotating the drill so the pins used to drive the ball lock cam fall into place around the ball

lock cam drive features on the bit box. Flexures on the bit box accommodate any misalignment. The SAT is then translated slightly further to preload the CBA into the bit box until a contact switch at the base of the bit box is triggered. The drill rotates to operate the ball lock in the bit box until the CBA is locked, disengages the magnetic chuck to release the CBA, and then retracts from the bit box. A similar procedure is followed to attach to a new CBA. Fig. 25 illustrates the bit changeout operation.

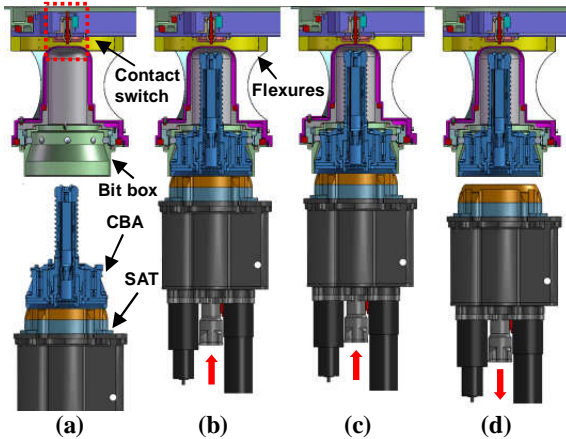


Fig. 25. Bit changeout operation: (a) CBA positioned under bit box, (b) CBA docked with bit box, (c) bit box preloaded, CBA locked into bit box, magnetic chuck disengaged, (d) SAT retracted

7.3 Sample Canister Removal

When the caching operation is complete, a spring-loaded cover above the canister carousel is released, as shown in Fig. 26. The robotic arm translates the SAT over the SHEC, attaches to the sample canister using the same magnetic chuck interface as the CBA, and removes the canister from the SHEC (see Fig. 27). The canister could then be placed on the ground with the robotic arm for possible retrieval later with a fetch rover during a Mars Sample Return mission.

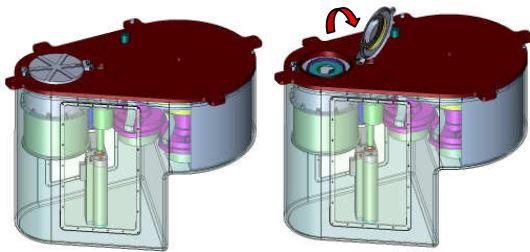


Fig. 26. Hatch opening for sample canister removal.

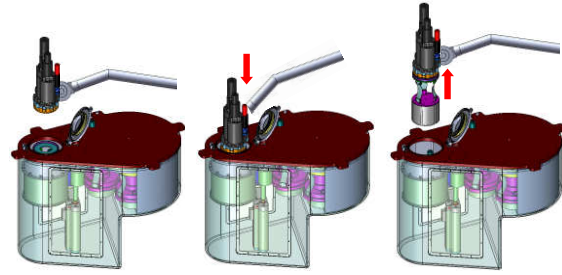


Fig. 27. Sample canister removal from the SHEC.

Fig. 28 shows a full view of the sample canister. Below the magnetic chuck interface is a set of flexures used to both preload the canister into the carousel and provide compliance when connecting with the magnetic chuck of the SAT. The sample canister itself is actually a “double wall” canister with an inner canister and an outer canister. The inner canister measures 7 cm in diameter and 7.5 cm tall, and would be the actual part of the assembly that goes into the OSC for sample return. The outer canister’s purpose is to “break the chain” between the contamination of the sample canister and Earth Return Vehicle and would be removed during transfer of the inner canister to the OSC, as described in [10] and [12].

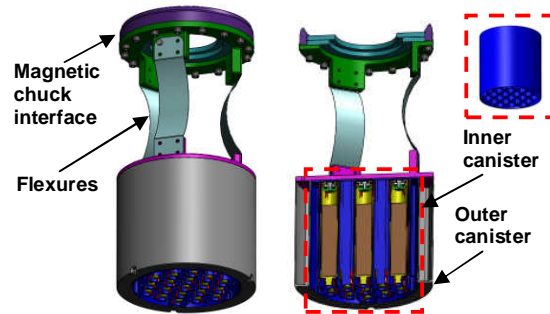


Fig. 28. Sample canister diagram.

8. ALTERNATE SHEC CONFIGURATION

The current SHEC prototype configuration contains one sample container with 19 sample tubes, 2 spare tubes, and 4 CBAs. Flexibility in the design allows expansion of the SHEC system to also include additional canisters, spare sample tubes, and specialized tools compatible with the SAT. With additional mass and volume availability the canister and bit carousels could be expanded to hold more sample tubes and bits, as shown in Tab. 2. If specialized tools for the SAT are desired (such as a soil sampling bit, a rock abrasion tool, or interface tool to accept samples for another rover), they could be integrated onto the SHEC bit carousel.

Table 2: Carousel variations for the SHEC subsystem.

Configuration	Layout	Number of Bits	Number of Tubes	Comments
Full Version		6	31 sample tubes 31 plugs 24 spare tubes 17 spare plugs	Large sample storage, large bit storage, most room for drill interface
Reduced Bit Carousel		4	31 sample tubes 31 plugs 24 spare tubes 17 spare plugs	Large sample storage
Reduced Bit and Canister Carousel		4	19 sample tubes 19 plugs 2 spare tubes 2 spare plugs	Smallest footprint
Single-Combined Carousel		4	19 sample tubes 19 plugs 11 spare tubes 11 spare plugs	Requires 1 less actuator, least room for drill interface

The SHEC subsystem could also be expanded to multiple sample canisters, as shown in Tab. 3. This option allows for increased sampling capability, addition of contingency sample canisters, and system redundancy for mission critical components.

Table 3: Multiple sample canister options.

Configuration	Layout	Number of Tubes
Single Canister		19 sample tubes 19 plugs 2 spare tubes 2 spare plugs
Dual Canister		38 sample tubes 38 plugs 4 spare tubes 4 spare plugs
Triple Canister		57 sample tubes 57 plugs 6 spare tubes 6 spare plugs

The current SHEC housing uses a vertical docking configuration for bit change-out and sample transfer operations. The benefit of this orientation is that the sample tube is always upright, taking advantage of gravity to reduce the risk of the sample spilling out of the tube. In the case of kinematic limitations of the arm or mounting of the SHEC to the rover body, the bit boxes could be angled on the carousel to allow for angled SHEC-SAT docking, as shown in Fig. 29.

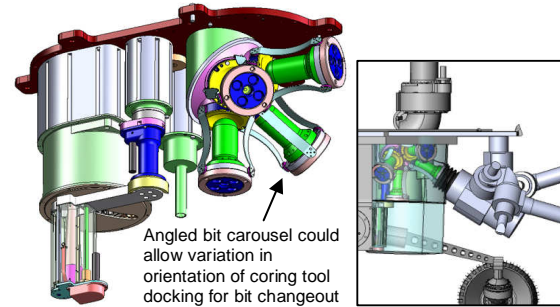


Fig. 29. Angled bit carousel adds flexibility to docking.

Assuming a 7 cm wide canister and 1 cm wide cores, a 19 sample hex pattern was chosen for close-packing the sample tubes. With different size core samples and canister diameters, other packing configurations are available, as shown in Fig. 30. 13 mm cartridge holes were chosen for 10 mm samples with a 0.75 mm min wall thickness to provide necessary volume for the sample tube thickness, retention fingers, lead-in chamfers, and structure.

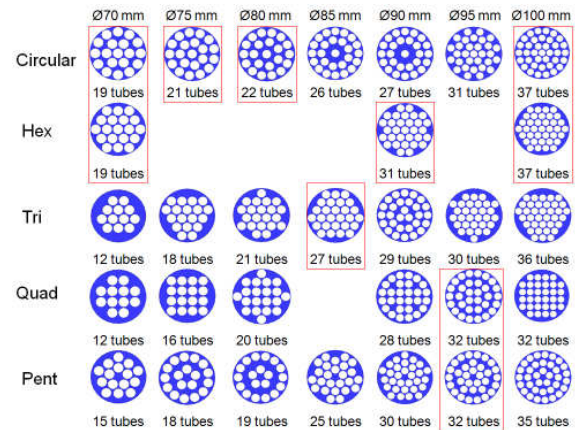


Fig. 30. Sample tube packing examples for various sample canister diameters using Ø13 mm cartridges.

Other SHEC configurations looked at include modifications to drop the canister onto the ground in cases where the arm cannot be used remove the canister from above.

9. SHEC PROTOTYPE AND TESTING

A proof of concept prototype of the SHEC subsystem was built and tested at the Jet Propulsion Laboratory. The prototype, shown in Fig. 31, contains a fully motorized sample carousel, bit carousel, handling arm, linear actuator, and tube gripper. Hall sensors were mounted to the assemblies for home positioning and limit switching. A force-torque sensor mounted at the base of the handling arm provides force measurements for tube transfer and sample sealing operations. Fully

automated tube transfer of 12 mm OD sample tubes were done between the sample canister and bits.

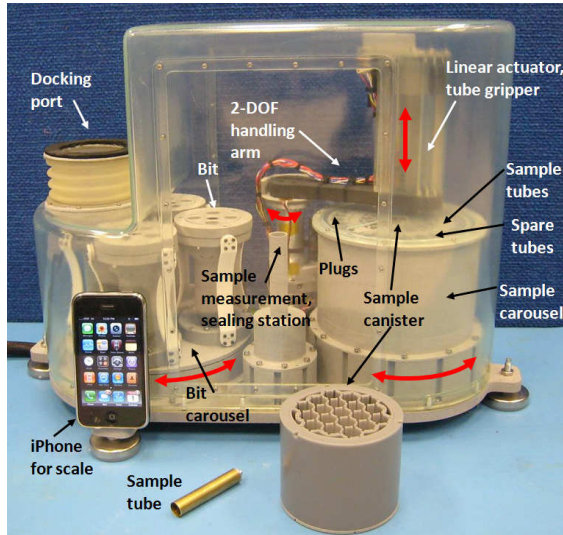


Fig. 31. SHEC prototype used for initial testing.

A TRL 4 level (breadboard validation in laboratory environment) design is currently in development at the Jet Propulsion Laboratory. Upon assembly, subsystem level testing will be performed, as well as end-to-end sample acquisition and caching with a TRL 4 SAT on a rover mounted robotic arm.

10. CONCLUSION

A Sample Handling, Encapsulation, and Containerization (SHEC) subsystem capable of sample caching functions for proposed future Mars sample caching missions such as MAX-C is being developed through the IMSAH task at the Jet Propulsion Laboratory. The SHEC subsystem provides a means to cache samples with a reduced risk to contamination, is robust to broken cores, enables close packing of the sample tubes in a sample canister compatible with current Mars Sample Return architectures, and could lead to a simplified and lighter drill without the need for a push rod to eject raw cores nor a gripper to hold tubes. Flexibility in the design allows expansion of the SHEC system to also include additional canisters, spare sample tubes, and specialized tools compatible with the Sample Acquisition Tool (SAT). A proof of concept prototype of the SHEC subsystem was built and tested, and a TRL 4 level design is currently in development.

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